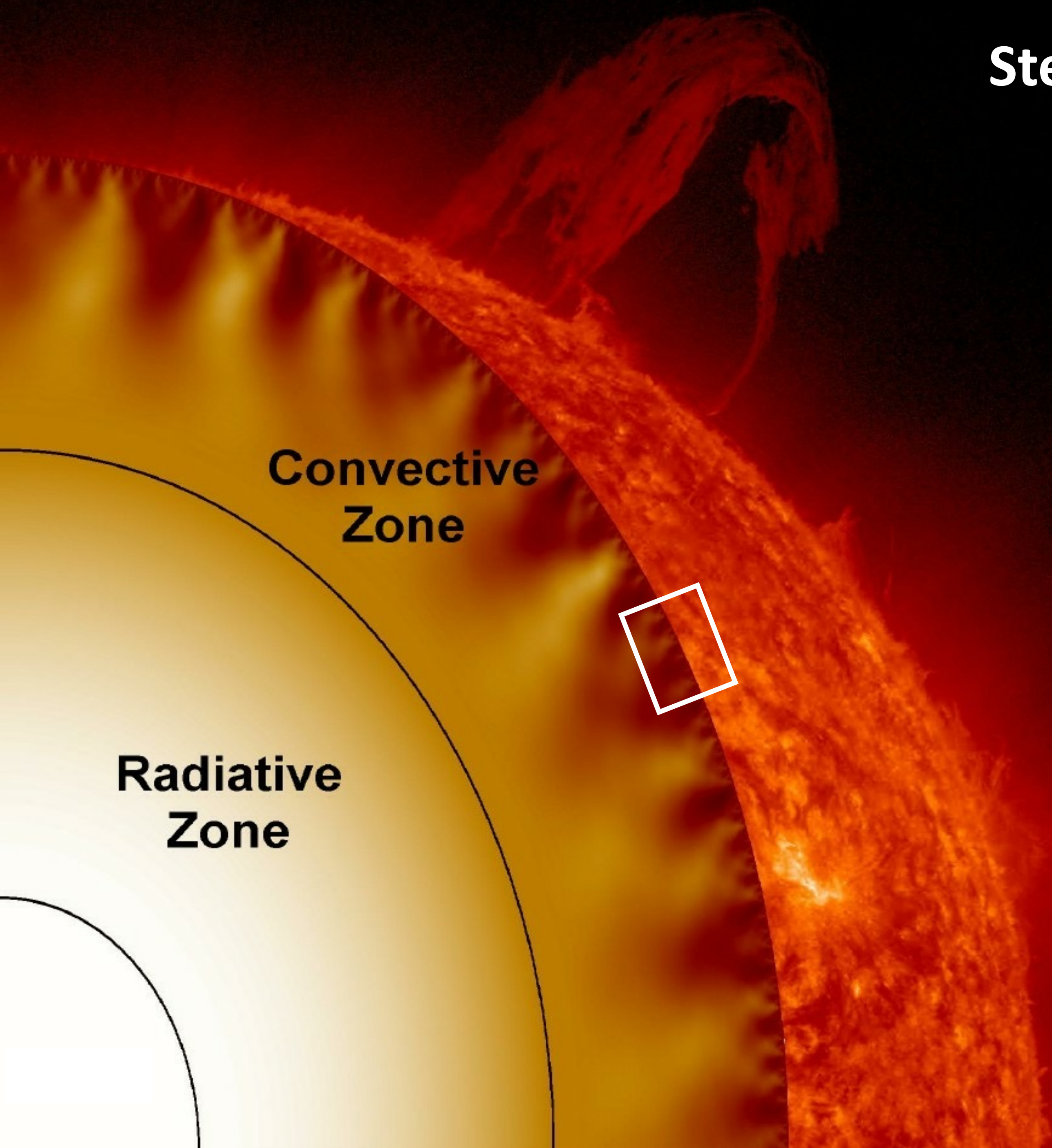
3D Realistic Modeling of the Sun and Solar-type Stars to Support Disk-Integrated Observations

Irina Kitiashvili[1], Samuel Granovsky[1,2], Alan Wray[1], Sage Li[1,3] , Kyla Mullaney[1,4]

[1]NASA Ames Research Center, [2]New Jersey Institute of Technology,

[3]Georgia Institute of Technology, [4]University of Chicago

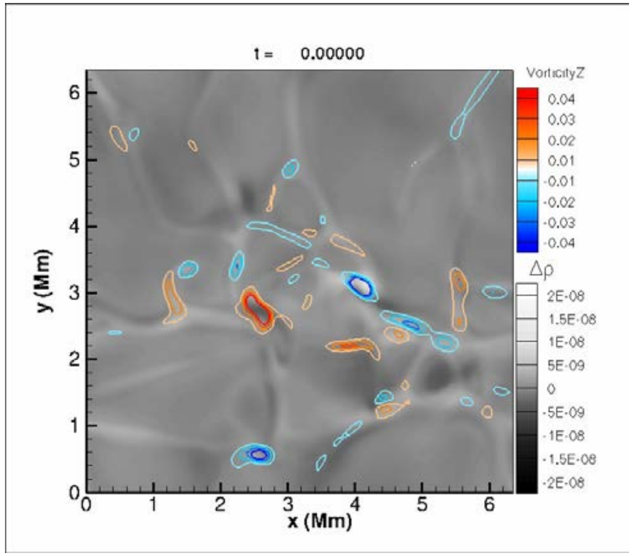
StellarBox code (Wray et al., 2015; 2018)



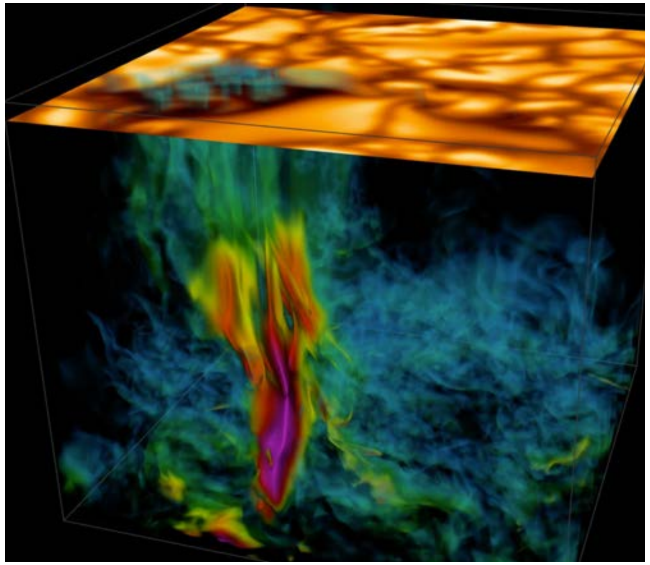
- Compressible plasma flows in a highly stratified medium
- 3D multi-group radiative energy transfer between the fluid elements
- Real-gas equation of state
- Ionization and excitation of all abundant species
- Small-scale turbulence
  - LES: Smagorinsky model (including its dynamic form)
  - DNS + Hyperviscosity approach
  - MHD subgrid models
- Magnetic effects
- Rotation
- Internal structure
- Opacity tables

3D realistic modeling of the solar dynamics

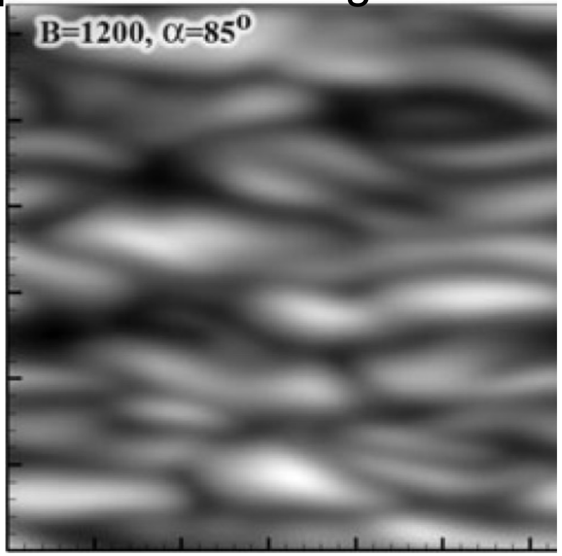
Acoustic waves excitation



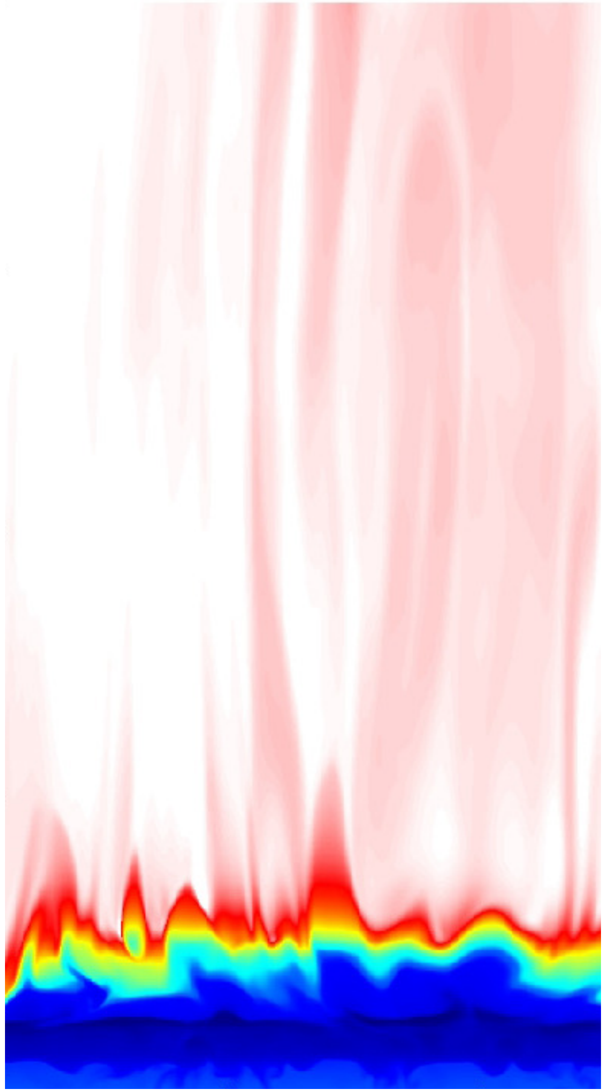
Magnetic structures formation



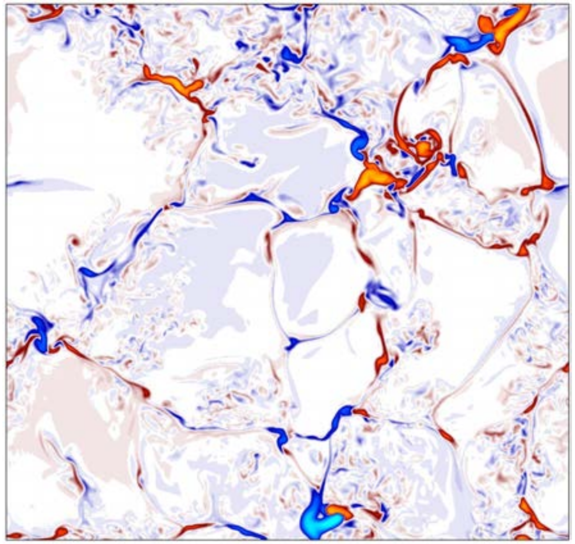
Self organization processes in magnetic field



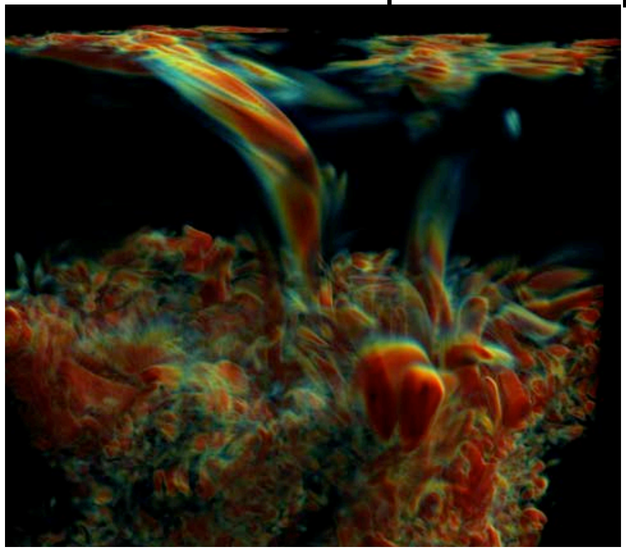
Solar corona structure and dynamics



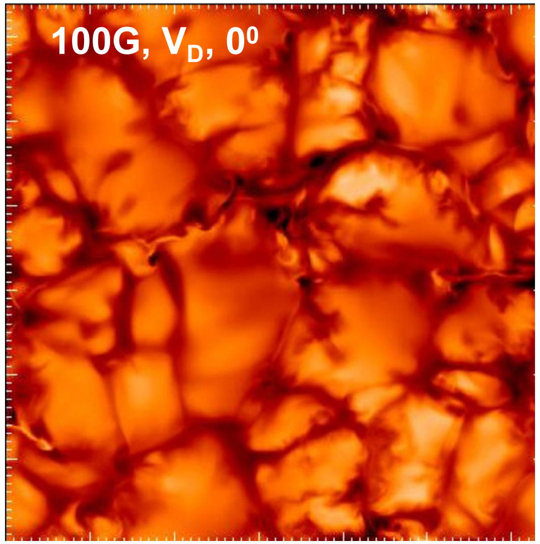
Small-scale dynamo



Jets and eruptions

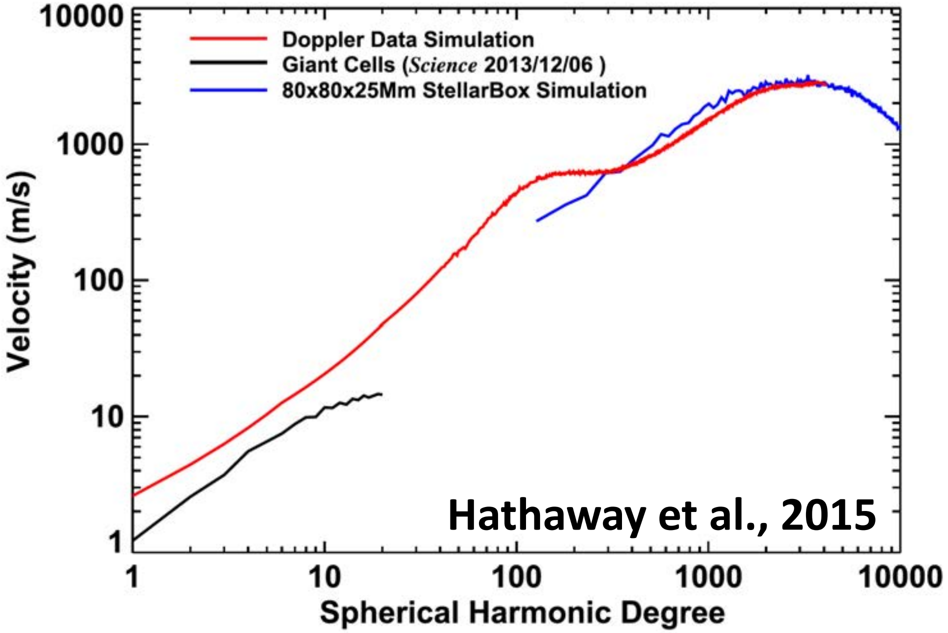


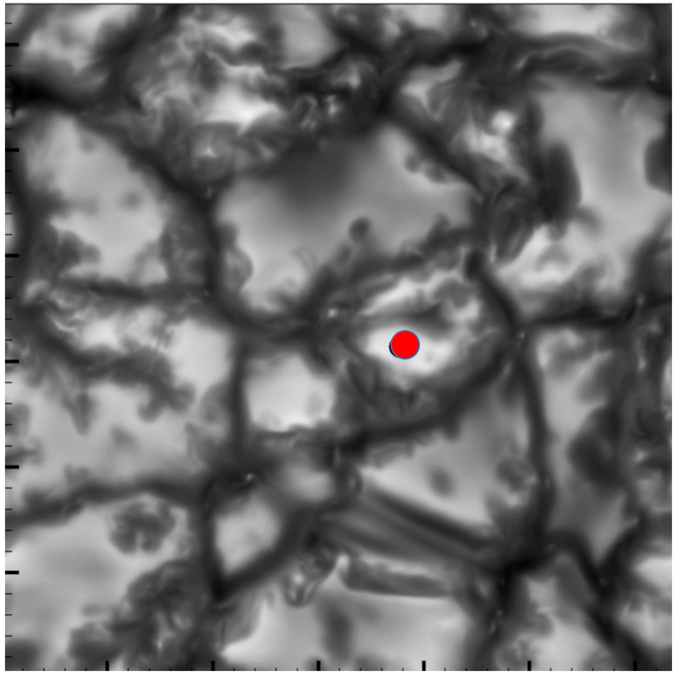
Spectral lines and observables

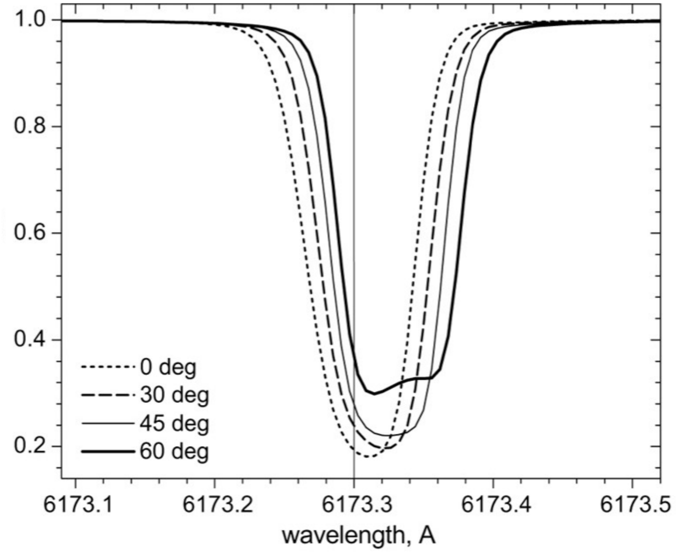


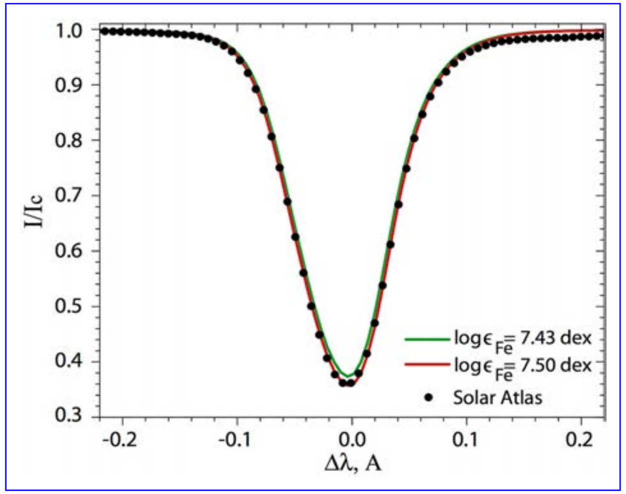
Kitiashvili et al., 2009-2023

Solar surface dynamics



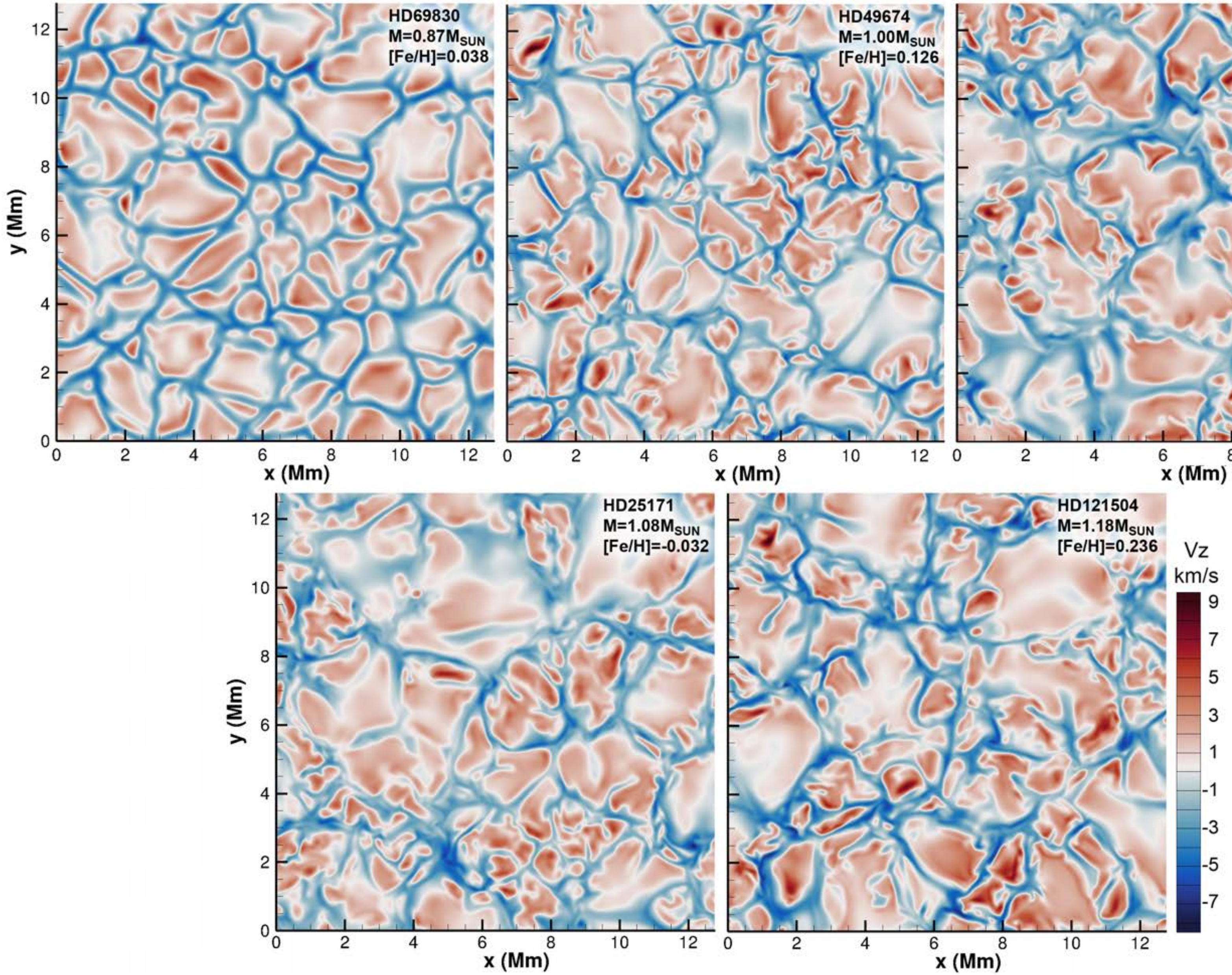






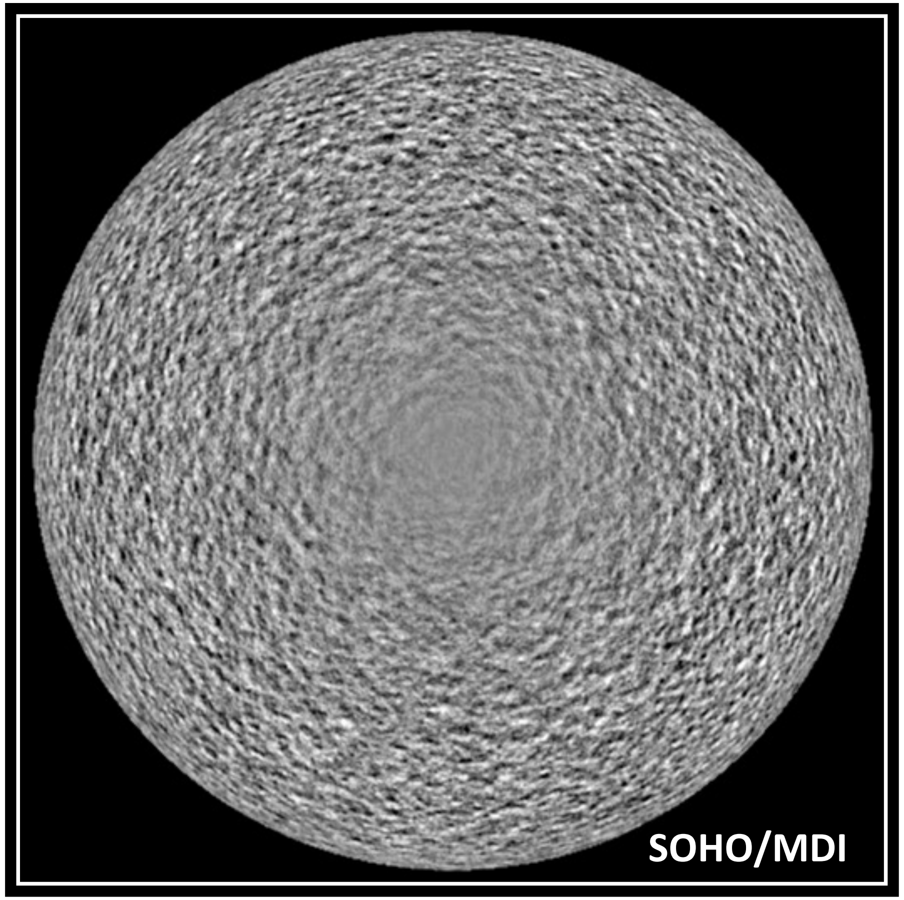
Kitiashvili et al., 2015

Granulation structure of the solar-type stars



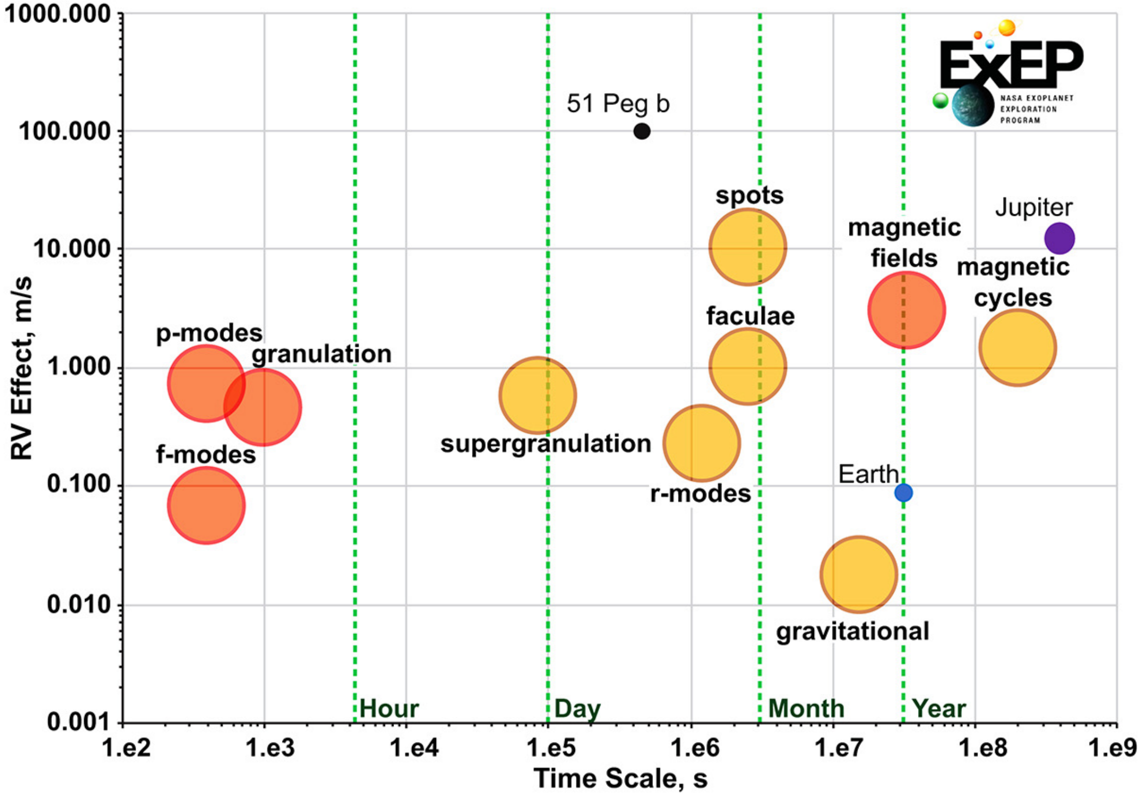
Our simulations show that the granulation structure on solar-type stars may be quite different from the solar granulation, and thus requires detailed modeling.

Contamination of the Radial Velocity Signal with Stellar Jitter



SOHO/MDI Dopplergram averaged over 30-min

Stellar jitter sources: p-, f-modes, granulation flickering, and magnetic fields



Schematic representation of correlated noise sources in the RV measurements originating from stellar surface convection and magnetic activity (modified from NASA EPRV working group report).

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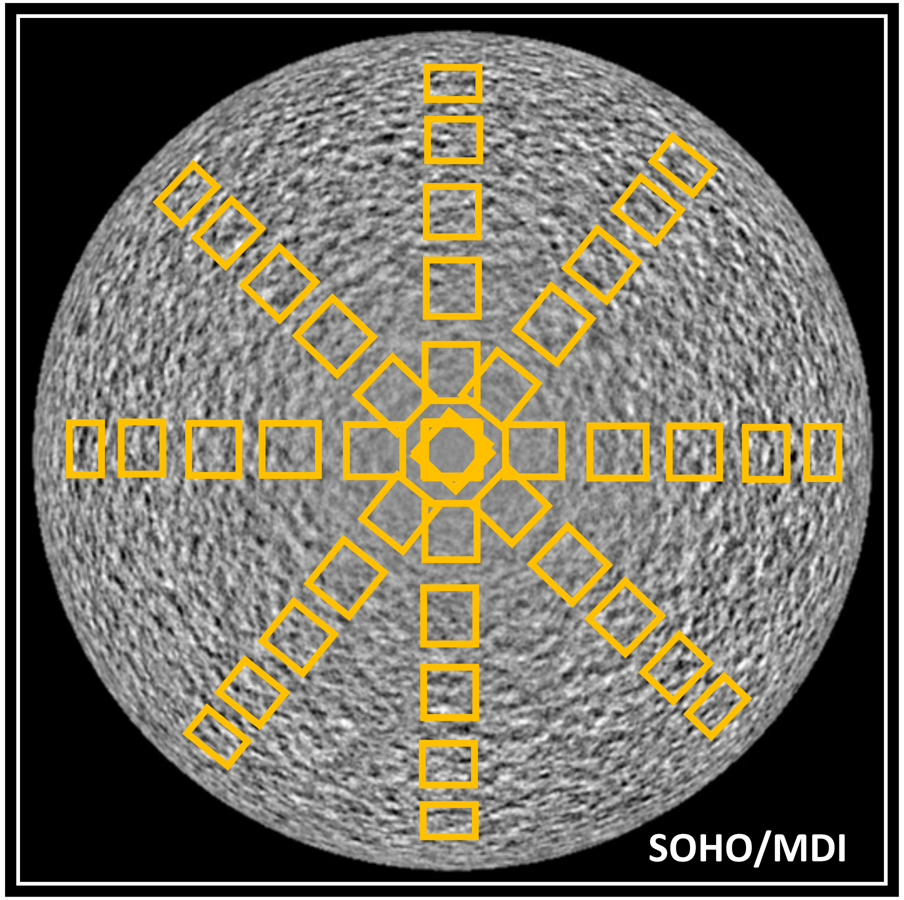

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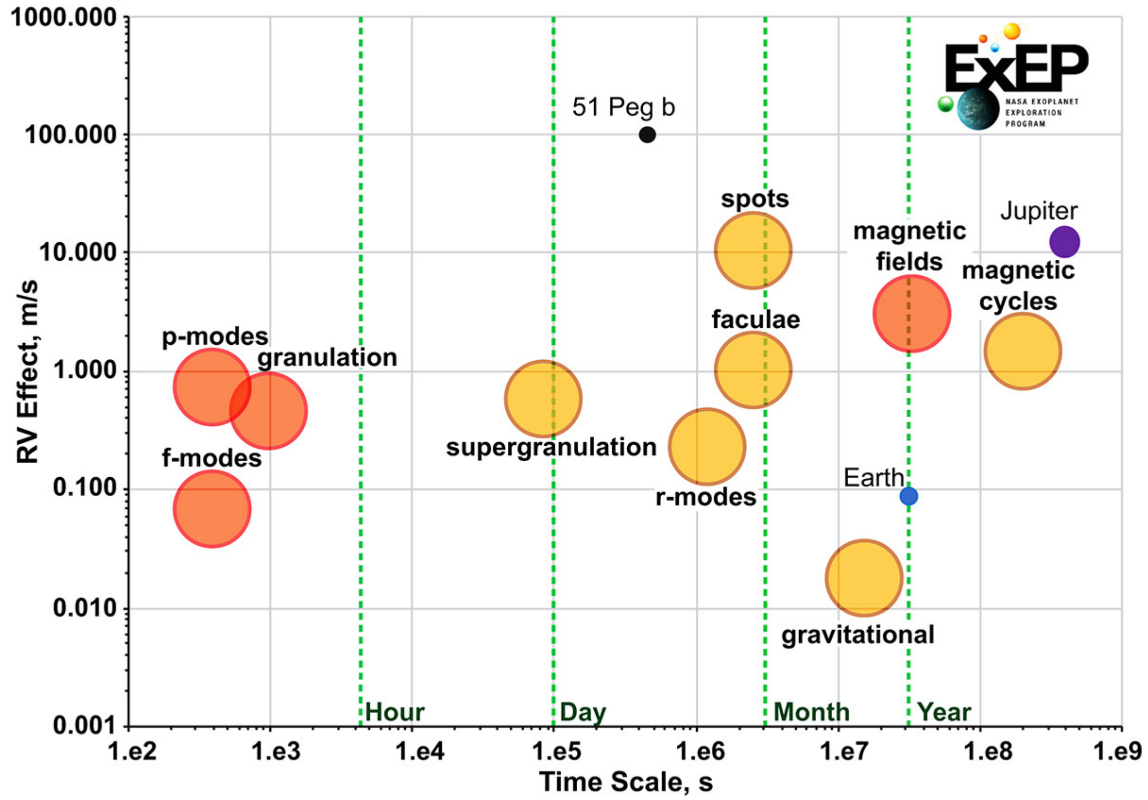

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Modeling Disk-Integrated Spectra & Observables

StellarBox Code → **Spinor Code** → **Synthetic data** → **Post Processing Scripts** → **Timeseries + Disk Integrated Time-series**

StellarBox Code

3D radiative model of upper stellar/solar convection zone and lower atmosphere

Spinor Code

Computation of synthetic data for individual Fe-I line profiles at various locations on the stellar disk

Synthetic data

Fe-I Lines:

20 Strong & 20 Weak

Locations:

Every 15° in radial angle (0° - 60°) & every 30° in polar angle

Post Processing Scripts

Computation of data for each snapshot:

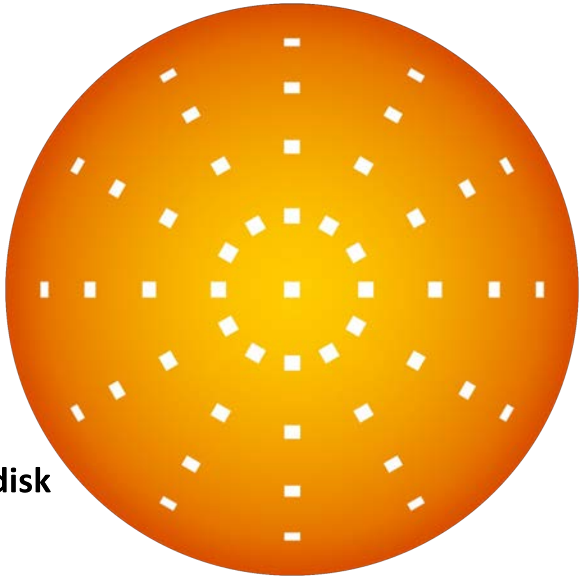
- Snapshot averaged spectrum
- Doppler Shift
- Continuum Intensity
- Line Depth
- FWHM
- Bisector

Timeseries + Disk Integrated Time-series

Weighted integration of synthetic data over entire stellar disk

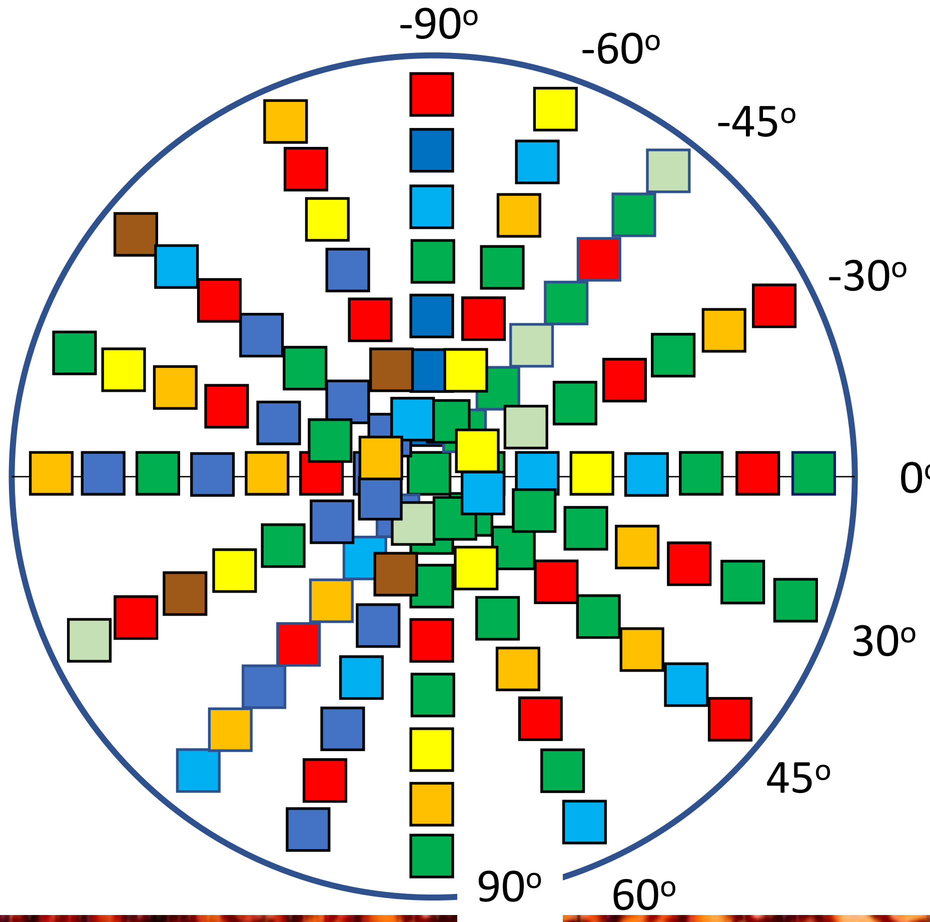
Observe changes in data over time

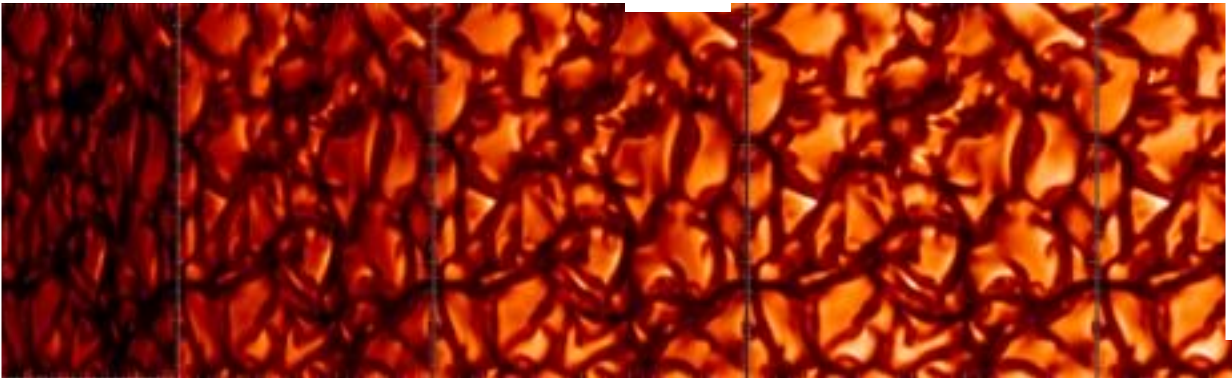
- Doppler Shift
- Continuum Intensity

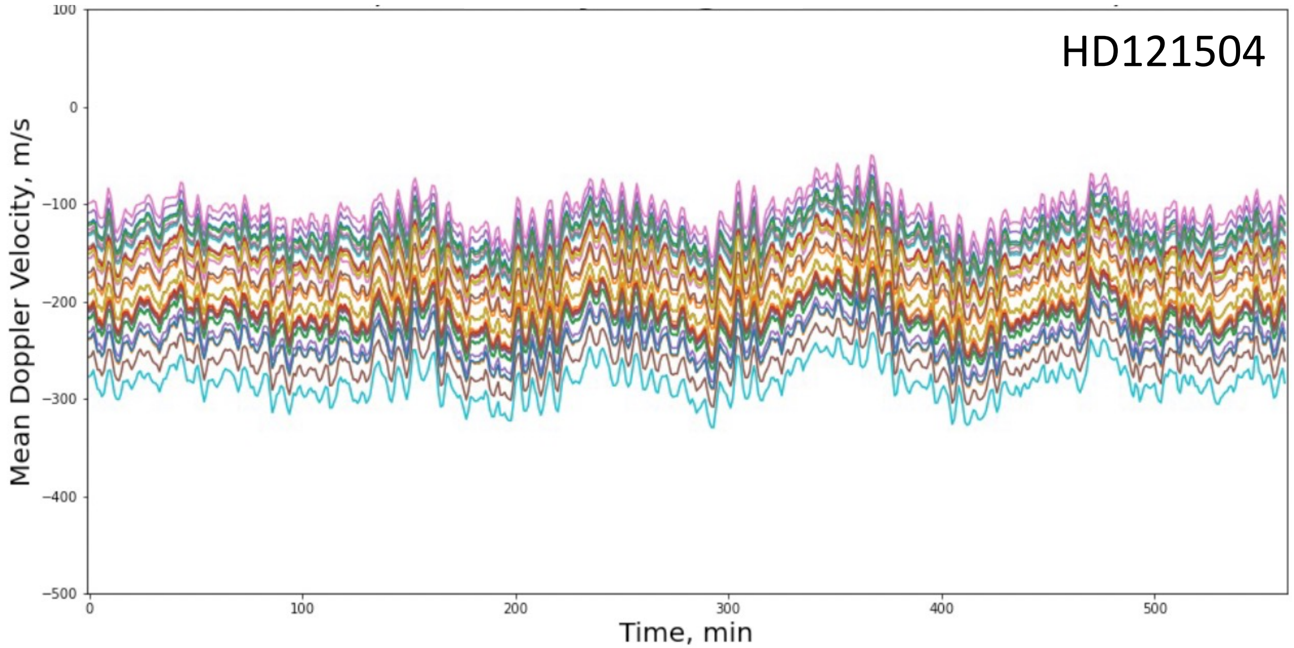


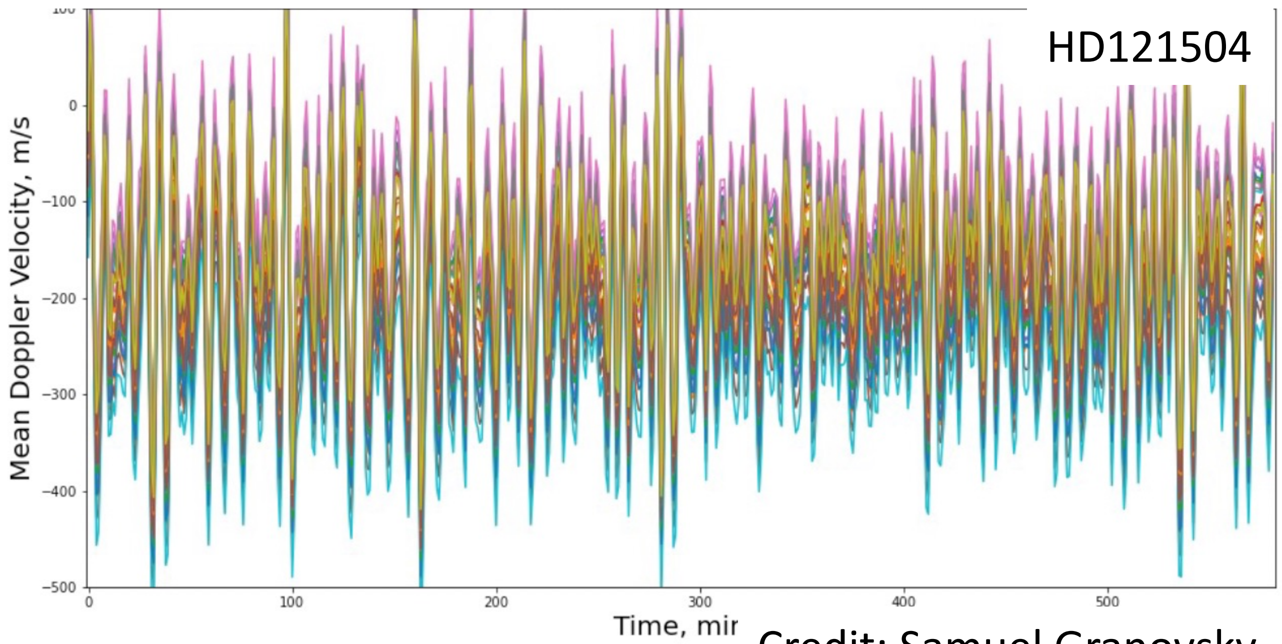
Locations of computed snapshots on solar/stellar disk

Modeling of Stellar Jitter





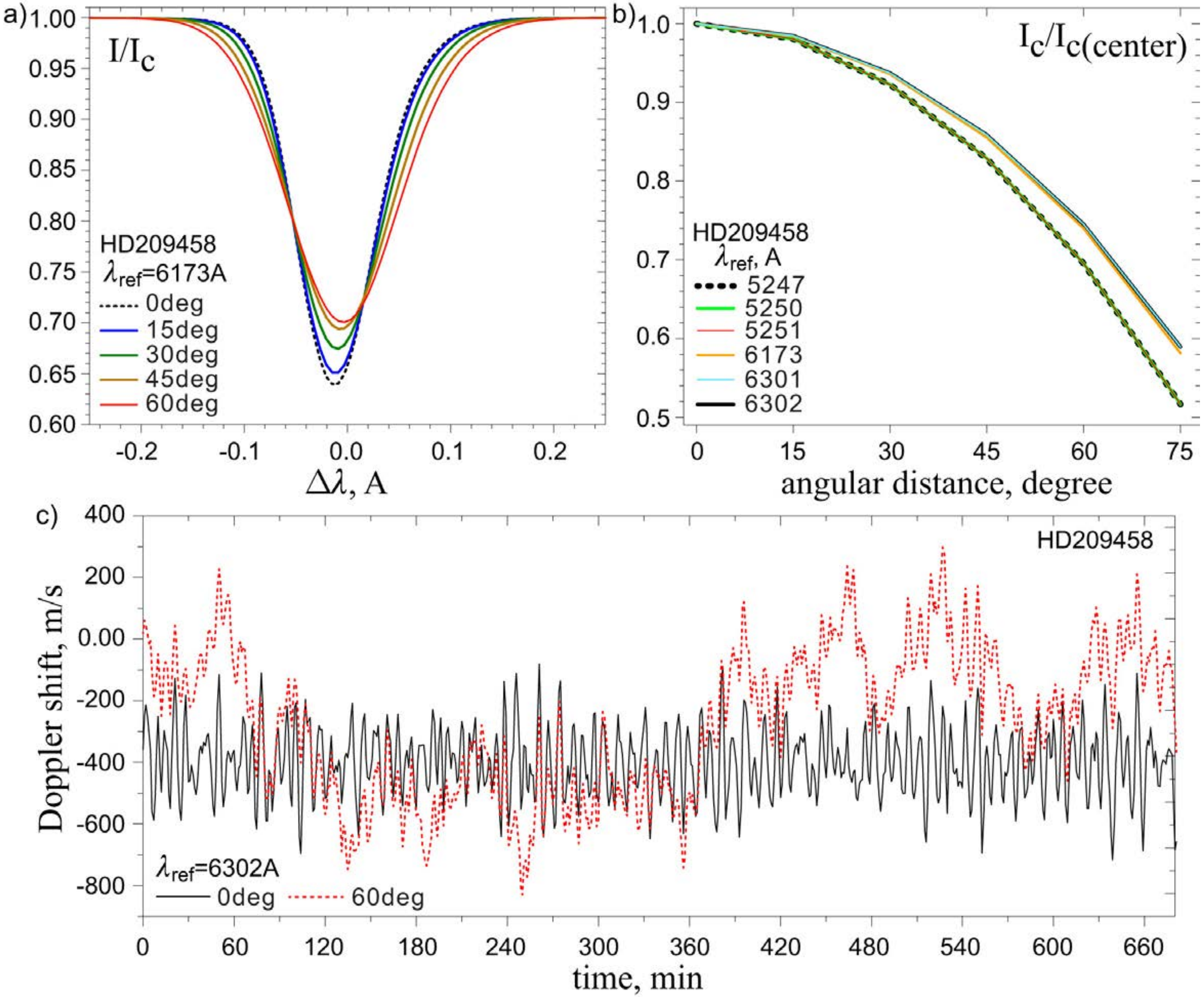




Credit: Samuel Granovsky

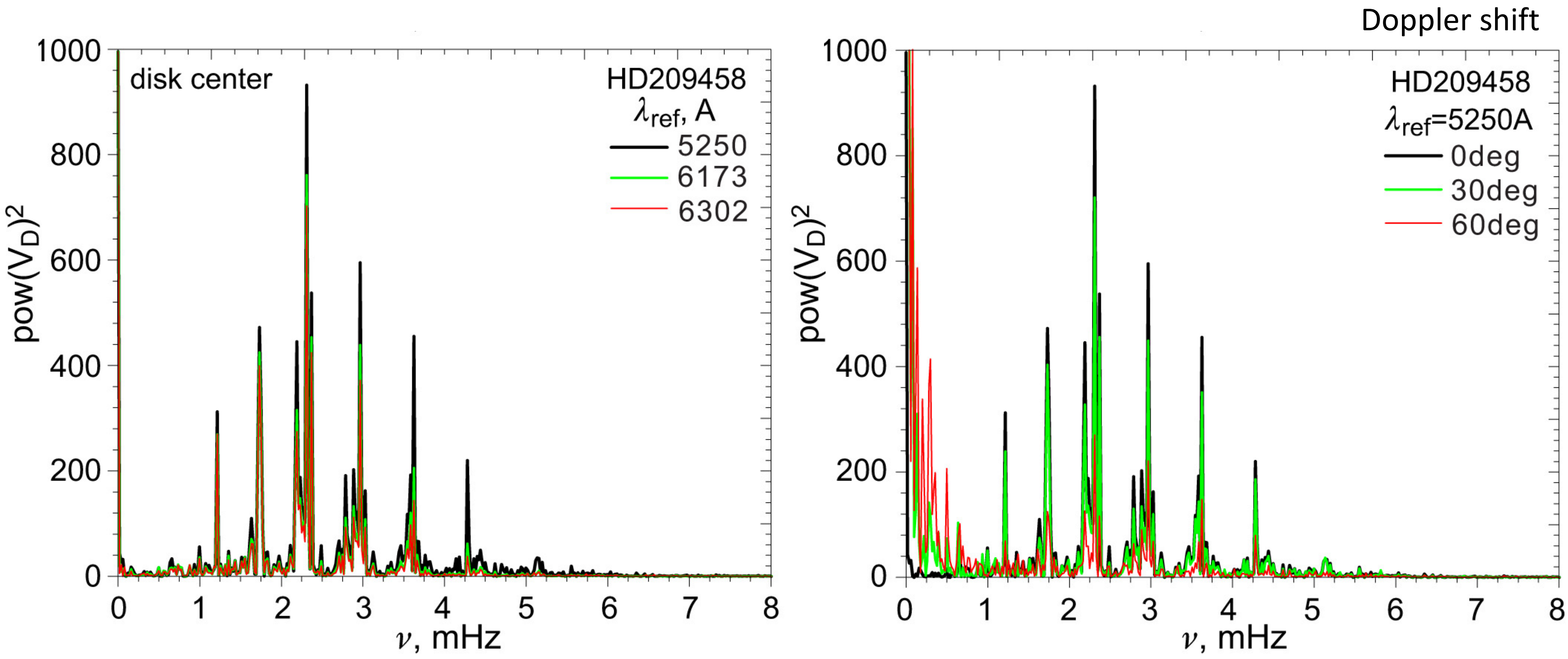

HD209458
Stellar surface dynamics reconstructed from synthetic continuum intensity patches

Planet-hosting star HD209458: center-to-limb effects



Center-to-limb effects:
a) changes in the spectral line (λref=6173A) at different distances from the disk center;
b) limb darkening profiles for six FeI lines;
c) Doppler shift variations as a function of time at the stellar disk center (black solid curve) and at 60 degrees from the disk center (red dotted curve).

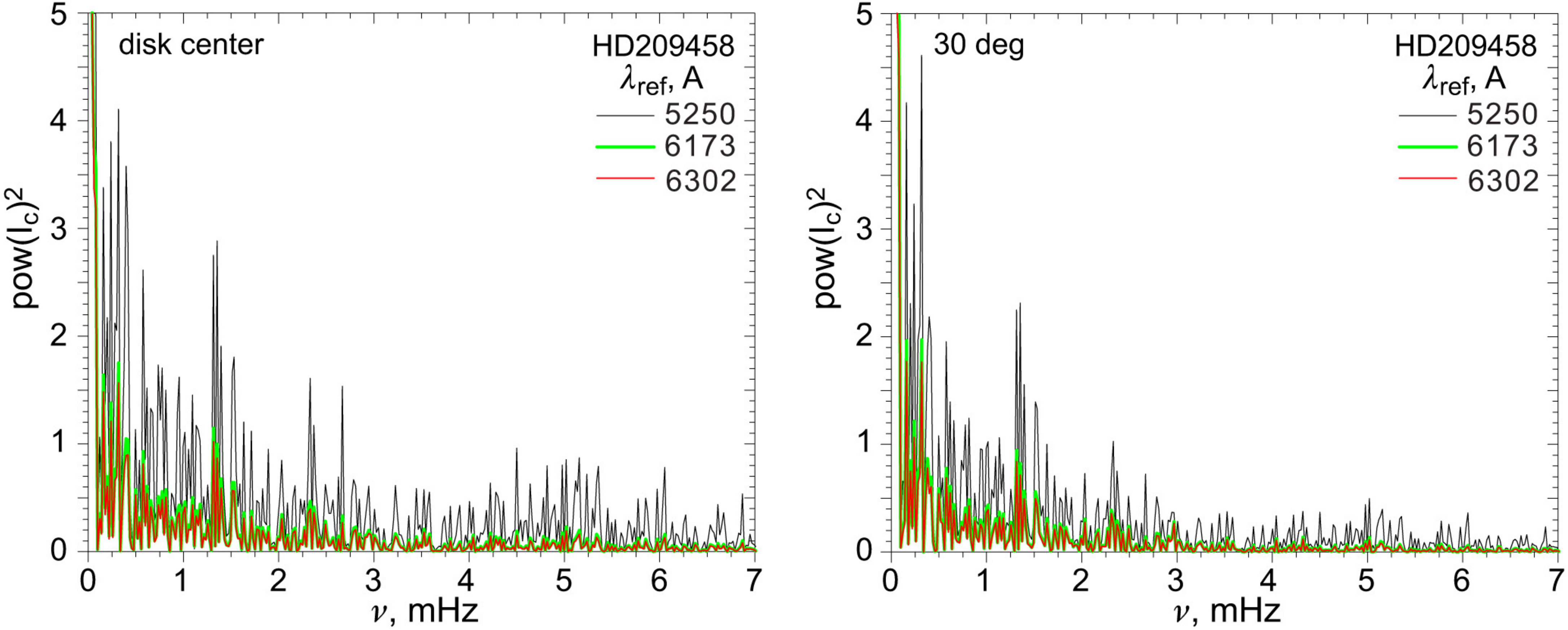
Planet-hosting star HD209458: oscillations



The power spectral density of the Doppler-shift corresponds to the simulated continuum intensity at the disk center computed from three spectral lines (left), and for three distances from the disk center (0, 30, and 60 degrees) for the single line 5250A (right).

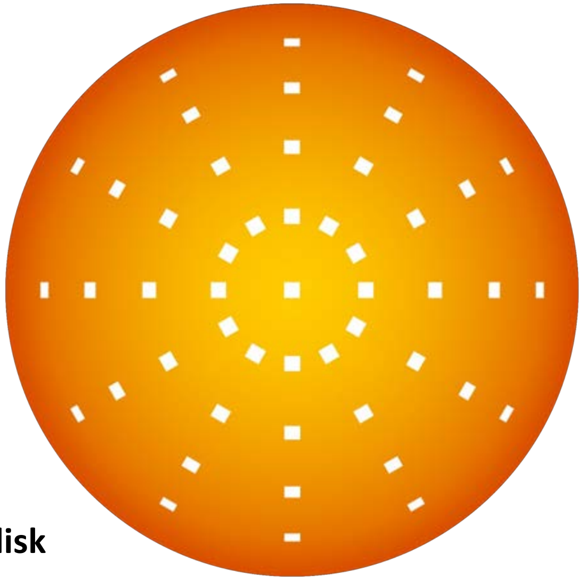
Planet-hosting star HD209458: oscillations

Continuum intensity

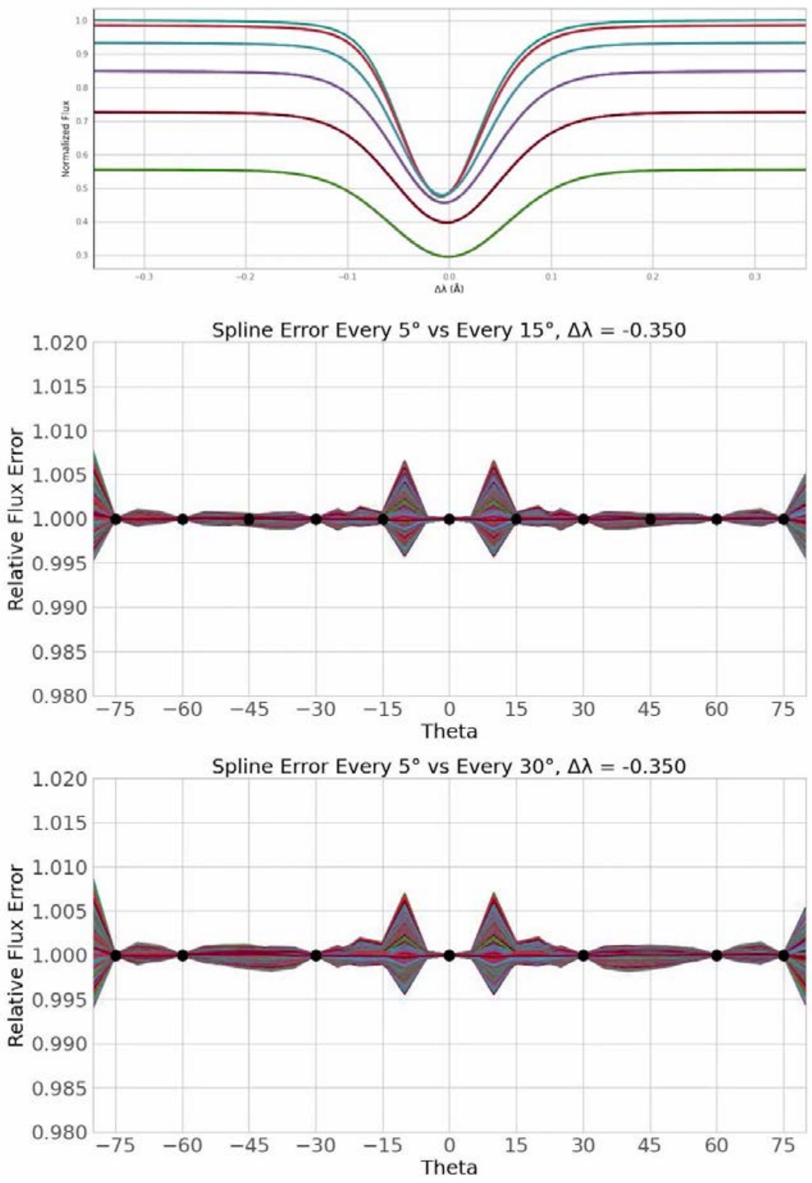


The power spectral density obtained from synthetic spectra of HD209458. The power spectral density of continuum intensity is shown for the disc center (left) and 30 degrees longitude (right).

Optimization of disk-integrated observables



Locations of computed snapshots on solar/stellar disk

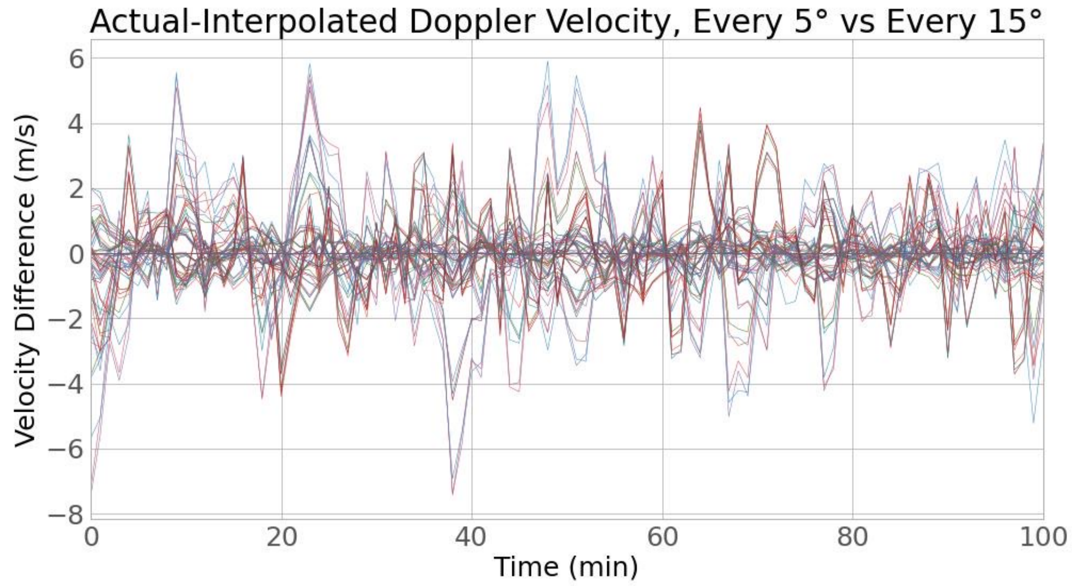


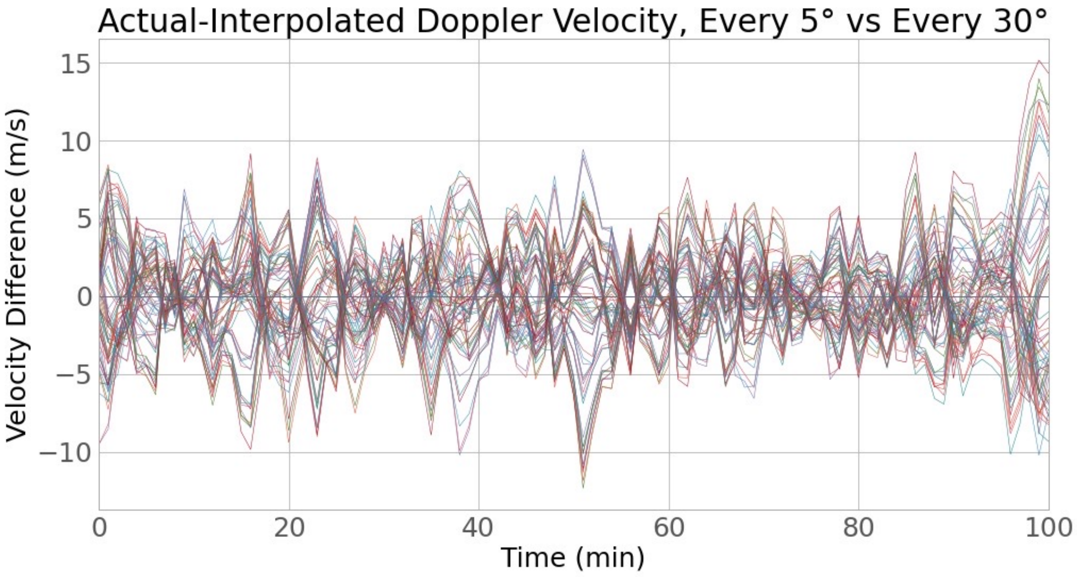
Tested for two sets of synthetic data and compared with every 5° in radial angle:

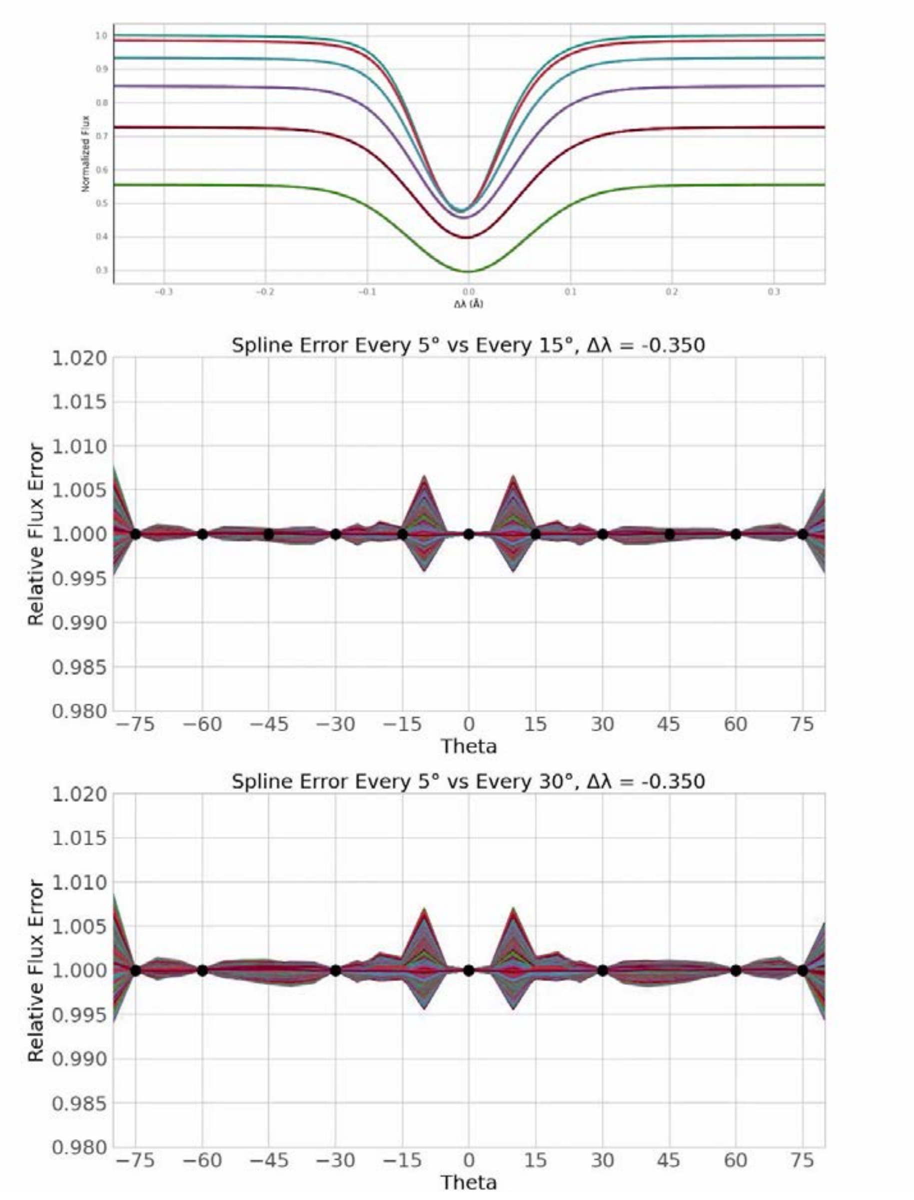
1) Every 15°: ±0.5% intensity error

2) 0°, ±30°, ± 60°, ± 75° (every 30°): ±1.5% intensity error

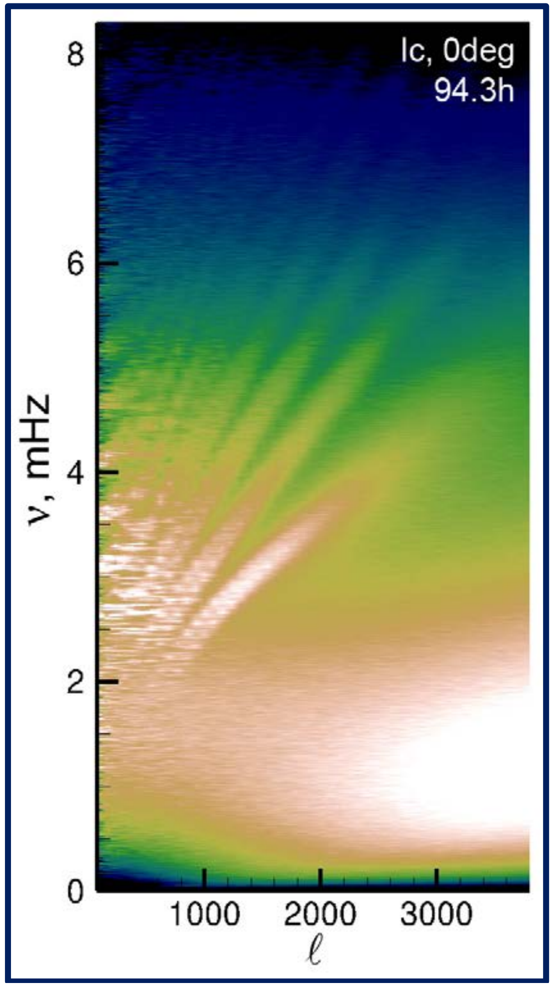
Optimization of disk-integrated observables



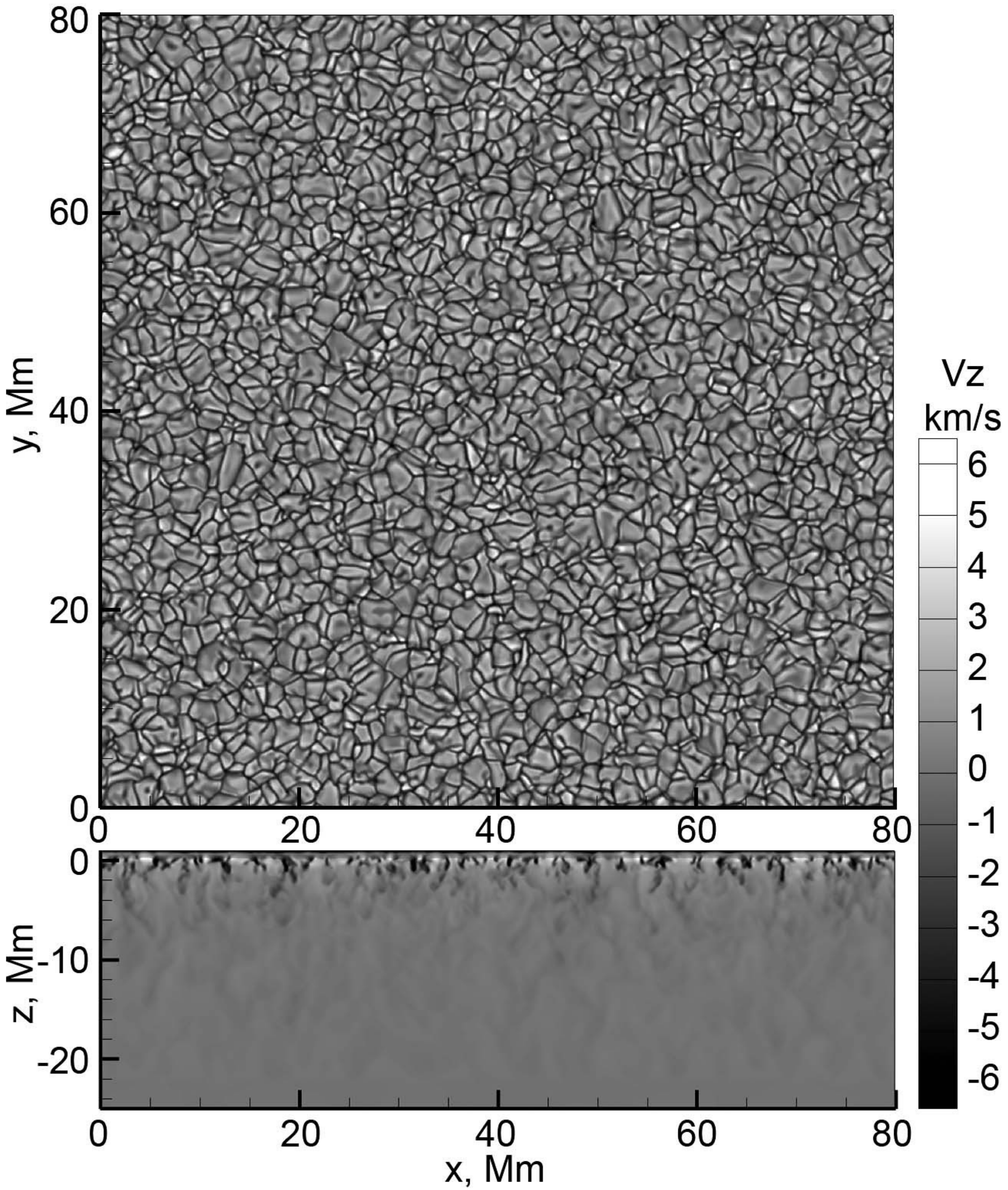




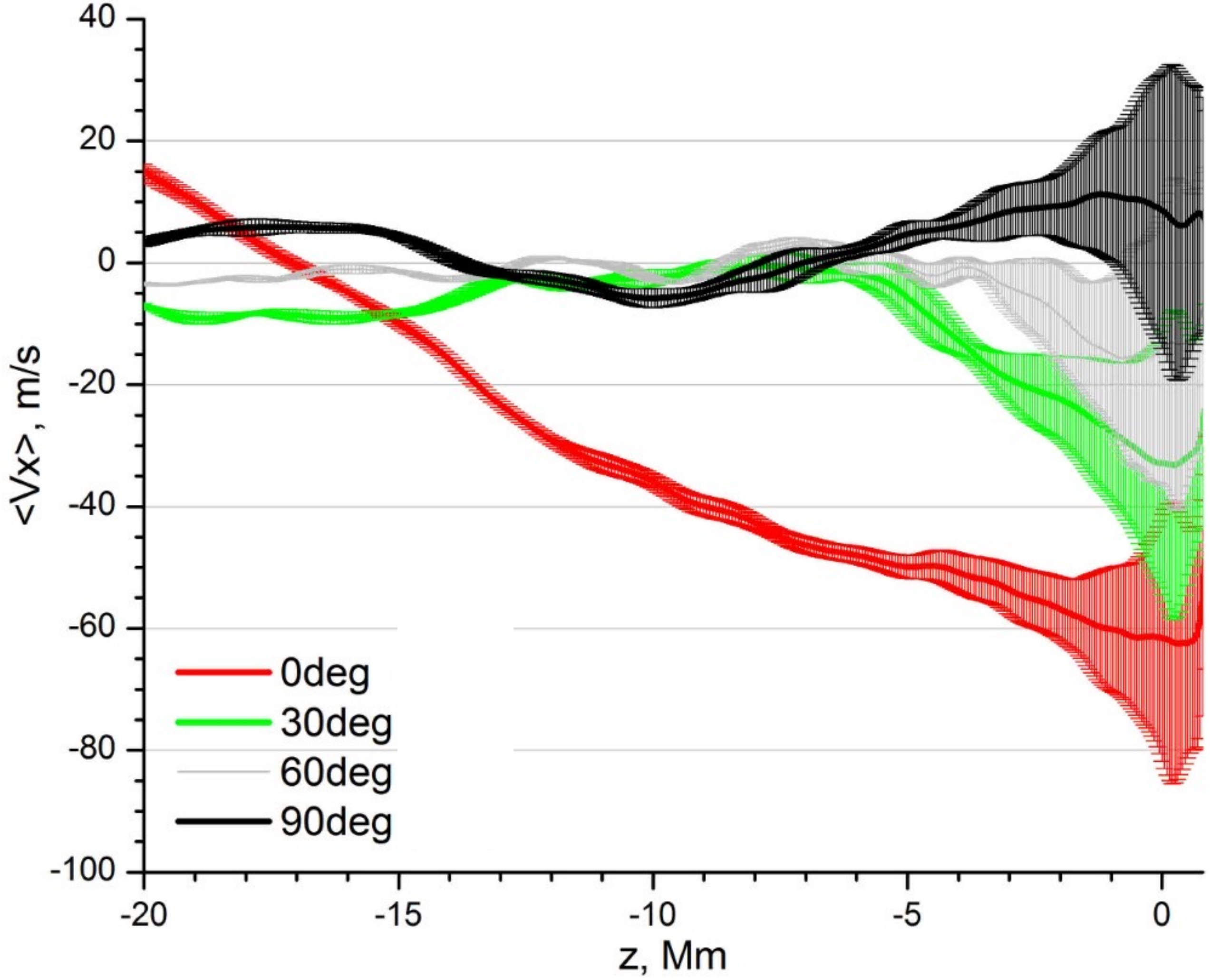
3D radiative MHD modeling in a local computational domain reproduces the solar convection and the oscillation spectrum



l-ν diagram computed using a 94.3 hour time-series of the continuum intensity (Fe I, 6173A) at the disk (Kitiashvili et al., 2023 in preparation)



Modeling the solar differential rotation at different latitudes



Conclusions

Our modeling of the Sun and solar-type stars allow us to investigate the nature of photospheric disturbances and its contribution to the disk-integrated observables

We have performed 3D simulations of convection for the Sun and solar-type stars with various mass and metallicity.

Developed a data modeling pipeline for massive line synthesis and computation of observables at different locations over the stellar/solar disk.

The results reproduce variations of spectral lines caused by convective motions and oscillations and allow us to investigate physical properties such as oscillation power spectra, center-to-limb variations of spectral line profiles, and convective blue shift, and start the development of physics-based filtering procedures.

❖ The work is supported by the NASA Extreme Precision Radial Velocity Foundation Science and Heliophysics Supporting Research grant